

Upstream LNG Technology
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Lecture – 32
Design of distillation column

Welcome, after learning about distillation and its construction now let us go to understand some of the basics of the analysis of the distillation columns for design purpose. So, in this particular lecture we shall be looking into Design of distillation column.

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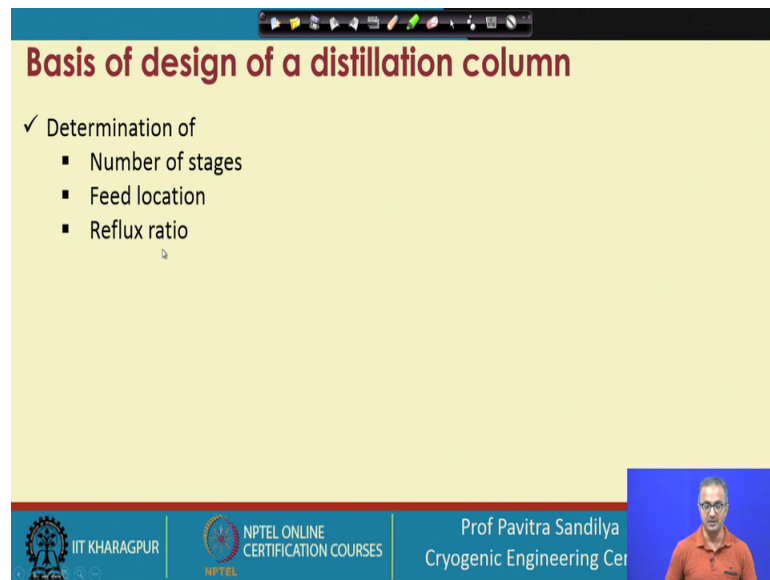
What we shall learn

- ✓ Stage
- ✓ An equilibrium stage
- ✓ Estimation of number of ideal stages

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And what we shall learn that we shall learn about the stages the equilibrium stages and the estimation of the number of stages.

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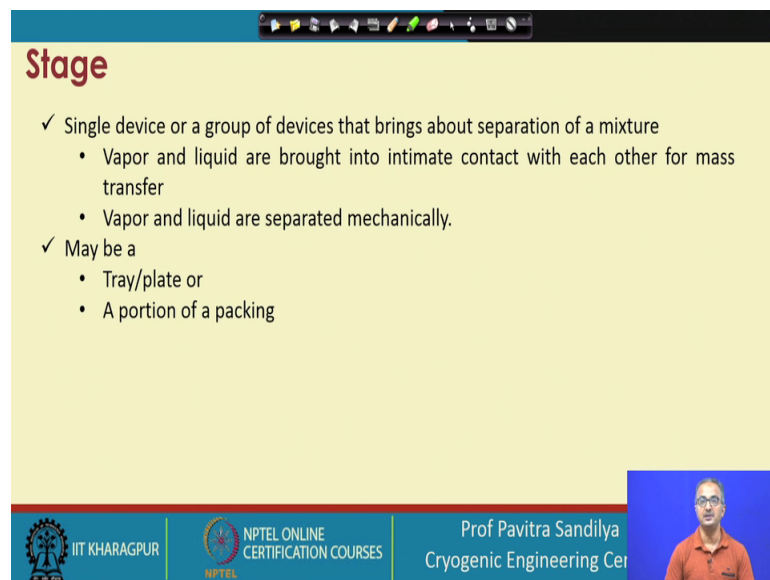
Basis of design of a distillation column

- ✓ Determination of
 - Number of stages
 - Feed location
 - Reflux ratio

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So, the basis of the design for these columns are that we determine the number of stages the location of the feed to the column and the reflux ratio.

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Stage

- ✓ Single device or a group of devices that brings about separation of a mixture
 - Vapor and liquid are brought into intimate contact with each other for mass transfer
 - Vapor and liquid are separated mechanically.
- ✓ May be a
 - Tray/plate or
 - A portion of a packing

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Now, first let us see what is a stage. Now stage is a single device or a group of devices, that brings about some separation to the mixture and in a stage what happens? First the vapor and liquid are brought into intimate contact, and then they are mechanically separated.

So, mechanically separated because unless we separate them out we cannot get a better product from the initial feed. So, the first of vapor liquid are intimately mixed and then there again physically separated, and this kind can be brought about as we learnt earlier by some tray or plate column plate or some packing.

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Stage

- ✓ Single device or a group of devices
 - Vapor and liquid contact
 - Vapor and liquid separation
- ✓ May be a
 - Tray/plate or
 - A portion of a packed column

2 Types of Distillation Columns
Examples of Distillation Column Internals

Sieve Tray

Tunnel Cap Tray

Bubble Cap Tray

Structured Packing

Source: GEA Wiegand GmbH, Ettlingen

[Prof. Dr. H. Kappas | Conceptual Design of Distillation, Absorption and Stripping Systems | 11]

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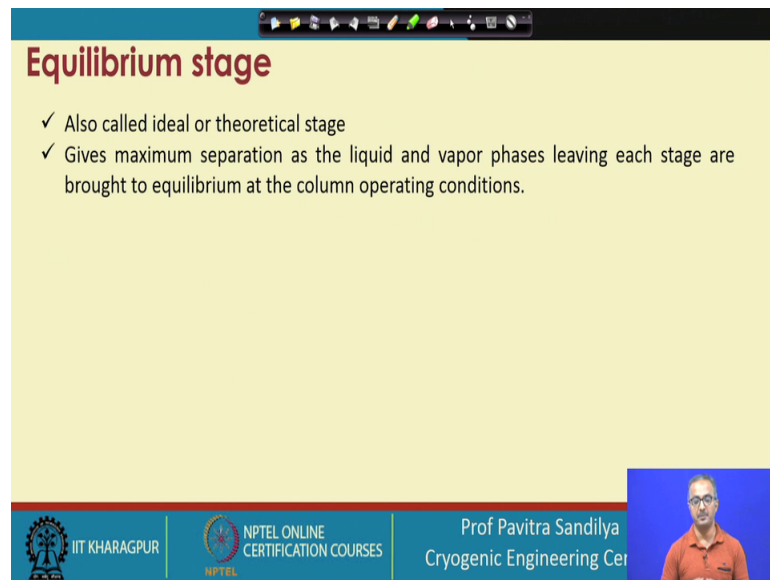
So, here as I showed you in the earlier lecture that we can have different types of tray Sieve tray, bubble cap tray, then tunnel cap tray, then the structured packings. So, these are the ones which are used to make these kind of stages. Please understand that stages are effective in bring amount about separation, but they do not represent any kind of physical entity that is why they are named at stage means a plate is not a stage ok.

So, we shall be seeing that how to convert the number of stages into the number of plates or trays or the pad column.

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Equilibrium stage

- ✓ Also called ideal or theoretical stage
- ✓ Gives maximum separation as the liquid and vapor phases leaving each stage are brought to equilibrium at the column operating conditions.



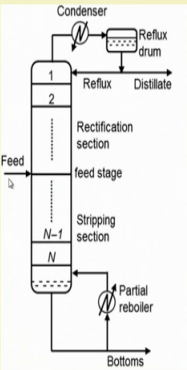
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So, now, next to come to the equilibrium stage and equilibrium stage is also called ideal or theoretical stage, and the name suggests that it gives the maximum separation between the liquid and the vapor because the liquid and vapor are so intimately contacted for a long enough time. So, that these 2 phases come to equilibrium and that that will give us the maximum possible separation under the given condition in the column, that is the pressure and temperature.

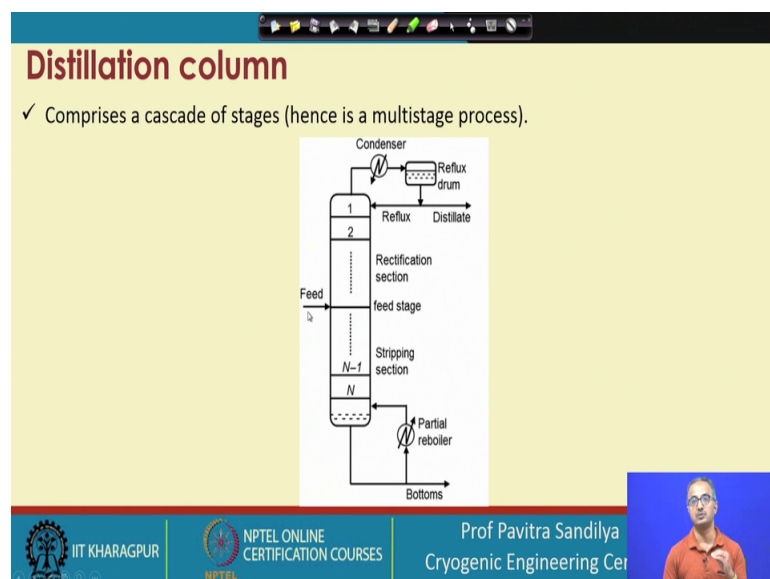
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Distillation column

- ✓ Comprises a cascade of stages (hence is a multistage process).



Condenser
Reflux drum
1
2
Rectification section
Feed
feed stage
Stripping section
N-1
N
Partial reboiler
Bottoms



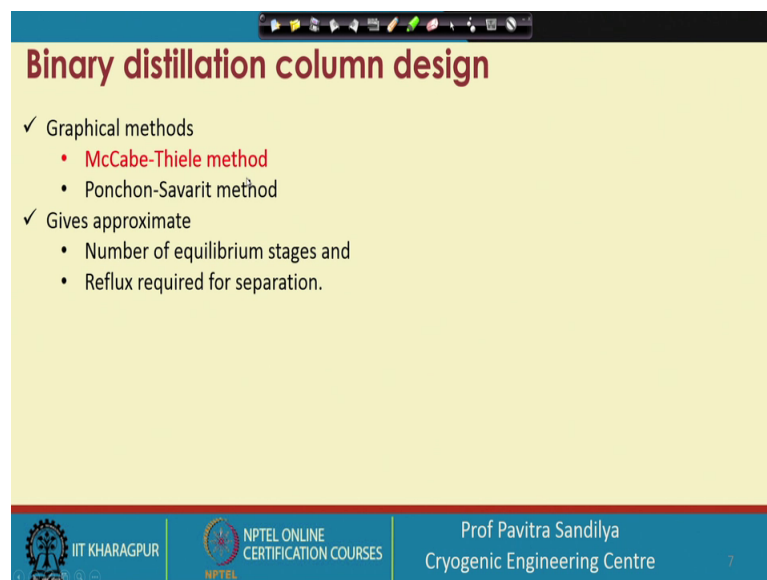
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And here we find that the column is taken to be comprising various stages that, earlier we found at the total column was given in terms of the trays or the packing, but now we are putting the column in terms of stages.

So, here we find the feed is going and the stage may be numbered from 1, 2 like that up to n, and the condenser is there and reflux drum and the reflux is coming here from the top and here if the liquid is going, it is getting vaporized in the partial reboiler and the liquid is taken out as a product and the vapor is going back to the column.

So, this is how this particular distillation column has been reduced in terms of the stages.

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Binary distillation column design

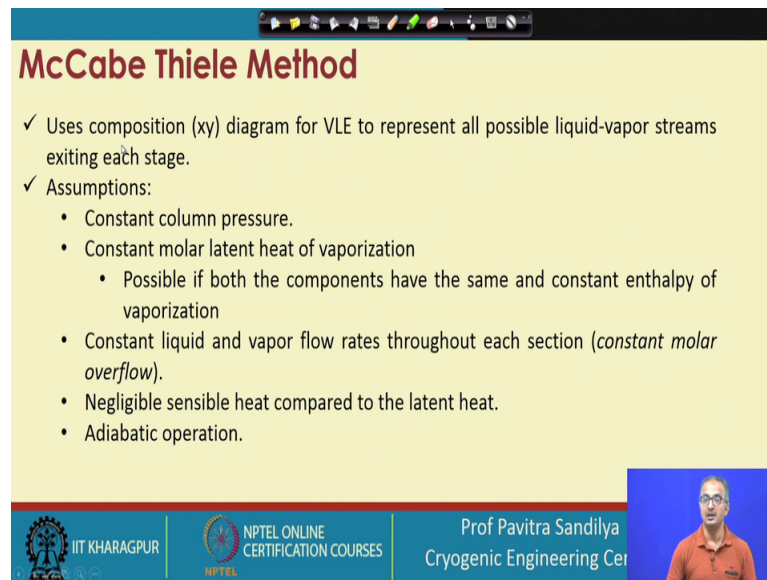
- ✓ Graphical methods
 - McCabe-Thiele method
 - Ponchon-Savarit method
- ✓ Gives approximate
 - Number of equilibrium stages and
 - Reflux required for separation.

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Now, we shall be concentrating on the binary distillation column design. There are various other methods for the multi component and which are not under the purview of this particular course, but a here we shall be looking into some binary column and this can still be used for multi component with some modifications.

So, let us see that how we design these kind of columns in this also we have 2 types which are very common one is the McCabe-Thiele method and there is a Poncho-Savarit method we shall be looking into the McCabe-Thiele method which is easier of the 2 and then we have after doing this design what we shall get? We shall get some approximate number of the equilibrium stages and the reflux required for the separation.

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The slide is titled "McCabe Thiele Method" in a red font. It contains a list of assumptions for the method, each preceded by a checkmark. The assumptions are: constant column pressure, constant molar latent heat of vaporization (with a sub-bullet stating it's possible if both components have the same and constant enthalpy of vaporization), constant liquid and vapor flow rates throughout each section (labeled as "constant molar overflow"), negligible sensible heat compared to the latent heat, and adiabatic operation. The slide footer includes the IIT Kharagpur logo, NPTEL Online Certification Courses logo, and the name of Prof. Pavitra Sandilya, Cryogenic Engineering Center.

McCabe Thiele Method

- ✓ Uses composition (xy) diagram for VLE to represent all possible liquid-vapor streams exiting each stage.
- ✓ Assumptions:
 - Constant column pressure.
 - Constant molar latent heat of vaporization
 - Possible if both the components have the same and constant enthalpy of vaporization
 - Constant liquid and vapor flow rates throughout each section (*constant molar overflow*).
 - Negligible sensible heat compared to the latent heat.
 - Adiabatic operation.

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So, let us now go for the McCabe-Thiele method; this McCabe-Thiele method is based on the equilibrium a composition diagram that is xy diagram for a vapor liquid equilibrium. Now there some assumptions in this McCabe-Thiele method first is that the pressure in the column is taken to be constant and the molar latent heat of vaporization of the liquid and the vapor are taken to be constant, and that is possible if the all the components can be assumed to have the same and constant enthalpy of vaporization.

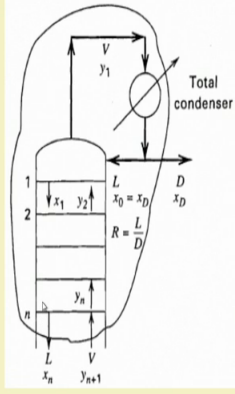
Then because of this constant enthalpy vaporization what happens that, for each mole of liquid vaporizing same number of moles is coming from the vapor to liquid phase ok. That means, what happens that whatever amount of liquid is lost due to vaporization, is compensated exactly by the amount of vapor that is getting condensed in that way what we find the liquid and the vapor which is which are going up and down, what we find the vapor that they have cause they are able to maintain constant flow rate throughout the particular other stages.

So, that is why we call the constant liquid and vapor flow rates throughout each section of the column, that is in rectifying section we have one liquid flow rate one vapor of flow rate and in the stripping section we have one liquid flow rate and one vapor flow rate, only thing is this the liquid flow rate in the stripping section and the rectifying section may or may not be constant.


Similarly, the vapor flow rate in the stripping section and the rectifying section may or may not be constant. We will see about this later on, but this particular assumption is called constant molar overflow and we assume that there is not a significant sensible heat transfer, and there is the total operation adiabatic that is there is no heat in leak or out leak from between the system and the surroundings.

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Rectification Section



- ✓ Stages are numbered from the top stage, 1, to just above the feed stage, f .
- ✓ Consider a portion of the rectifying section up to an arbitrary stage n including the condenser.
- ✓ Overall material balance:
$$V = L + D$$
- ✓ Component material balance w.r.t lighter component is
$$Vy_{n+1} = Lx_n + Dx_D$$
- ✓ Define **reflux ratio**, R : Ratio of the liquid refluxed to the distillate rate. Thus $R = L/D$



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Here we first consider the rectification section or the enriching section here we what we do, that we number the stages from top to bottom as 1 2 up to small n and this well this particular section comprises of the stage just above the feed stage. So, here; that means, this particular section will move just above the feed stage.

So, what we first do that first we choose this particular control volume, which is where having including this condenser and some nth number of stages and we as with them our nomenclature what we do that we put x_1 x_2 as the mole fraction of the liquid and y_1 y_2 as the mole fraction in the vapor, and in this case the subscript is corresponds to the stage number from which the particular stream comes out; that means, from the stage 1 this liquid is coming out. So, we are putting the subscript 1 to this x.

Similarly, when this liquid is coming out from the nth stage, we are putting the subscript n to this mole fraction of liquid similarly this vapor is coming out from the stage 2. So, we are putting 2 as a subscript 2 y and similarly here this particular vapor is coming out

from the n th stage. So, it is given as y_n . And here we have find that this, but because the number is increasing from top to bottom.

So, the vapor which is coming to the n th stage is taken to come out from $n + 1$ th stage. So, this particular mole fraction is given $n + 1$ as the subscript, and from top we find that the this vapor is coming from the first stage. So, it has been given the y_1 as the mole fraction and then the liquid which is going into the column as reflux it is taken to be coming out from a stage, which is zeroth. Zeroth does not exist physically, but as per nomenclature any stage that is above this first is taken to be 0.

So, we are giving this x_0 as the mole fraction of the reflux liquid and here we put x_D as the distillate composition, D is the m flow rate of the distillate L is the flow rate of the reflux and V is the flow rate of the vapor. So, with this nomenclature what we do, we take this particular control volume and makes the again we go back to our there is a mesh equations, which we learnt earlier. So, first we take the mass balance in the mass balance we find that V is equal to $L + D$ that is V is going in and L and D are coming out please understand all these balances are made at steady state.

So, this V is equal to $L + D$ and then what we do that V are put in making the component material balance, and we are writing the material balance in terms of the lighter component ok. So, we have the $y_{n+1} V$ into y_{n+1} is the molar flow rate of this lighter component is equal to $L x_n + D x_D$ is the molar flow rate of the lighter component and similarly plus $D x_D$ is the molar flow rate of the lighter component going out of the control volume.

So, that is how we are going for the component material balance, and then we define a reflux ratio R which is the ratio of the liquid reflux to the distal amount of distillate taken. So, this is taken as L/D .

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Rectification Section

- ✓ Solving for y_{n+1} ,

$$y_{n+1} = \frac{L}{V}x_n + \frac{D}{V}x_D$$
 - **Operating line equation:** Correlates the phase compositions of two passing streams (incoming vapor and outgoing liquid)
- ✓ Mass balance around the condenser:

$$V = L + D$$

$$\frac{L}{V} = \frac{L}{L+D} = \frac{R}{R+1} \text{ and } \frac{D}{V} = \frac{D}{L+D} = \frac{1}{R+1}$$
- ✓ Equation of operating line is given as

$$y_{n+1} = \left(\frac{R}{R+1}\right)x_n + \left(\frac{1}{R+1}\right)x_D$$

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So, with this definition of reflux ratio what we do we are reducing if the this particular equation as $y_{n+1} = \frac{L}{V}x_n + \frac{D}{V}x_D$.

Now, this particular equation what is it doing? It is correlating the composition of the 2 crossing stream, this they are these 2 they are passing by. So, these 2 composition of these 2 streams this y_{n+1} and x_n these compositions are being related by this particular operating line. And now we take the material balance around this condenser we find that V is going inside the condenser, and it is being split into 2 streams L plus D . So, we find that this V is equal to L plus D .

now we are doing as a bit of rearrangement here to find the value of L by V from this equation and we find L by V is equal to L by L plus D from this, and we then divide the numerator and denominator by D . So, L by we get L by D as reflux L by D as reflux R a plus 1. So, this L by V can be replaced by R by R plus 1.

Similarly, this D by V is taken as D by L plus D , again we divide by D . So, we get 1 by R plus 1. So, this D by V is now replaced by 1 by R plus 1. So, the operating now becomes why $n+1$ in terms of only reflux ratio and the distillate composition.

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Rectification Section

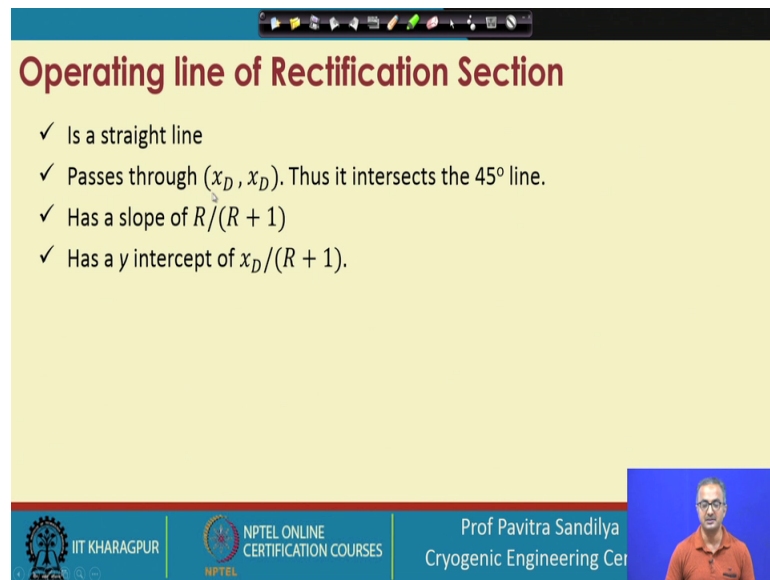
- ✓ Ratio $\frac{D}{V}$ may also be obtained from energy balance.
- ✓ Energy balance:
$$Vh_{V,n+1} = Lh_{L,n} + Dh_D + \dot{Q}_C$$
- ✓ Combining with the overall mass balance we get
$$\frac{D}{V} = \frac{h_{V,n+1} - h_{L,n}}{(\dot{Q}_C/D) + h_D - h_{L,n}}$$

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Now, we can also find out the D by V ratio from the our energy balance. So, if you take an energy balance, what we find that this is the amount of energy that is going n here the h is signifying the specific molar enthalpy and the subscript V is given to signify the vapor.

So, this is the total amount of enthalpy going into the system, and this is the enthalpy coming out with the liquid this is the enthalpy going out with the distillate and this is the condenser duty that is also taken; that means, we are we have to take out the energy from the vapor to liquefy it. So, these are condenser duty which is coming out of the system. Again when we rearrange this equation we get the expression for D by V; that means, D by V can either be obtained from the reflux ratio or from the energy balance.

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Operating line of Rectification Section

- ✓ Is a straight line
- ✓ Passes through (x_D, x_D) . Thus it intersects the 45° line.
- ✓ Has a slope of $R/(R + 1)$
- ✓ Has a y intercept of $x_D/(R + 1)$.

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Now we find that the operating line of the rectifying section is a straight line and it passes through this point x_D, x_D that we can find from here, that if I put this value of x_D here. If we put x_D here what we find that y_{n+1} will also be coming to x_D you can do it easily. So, $y_{n+1} = x_D$; that means, this operating line may it passes through x_D, x_D and because for a given operation R is constant. So, the slope is also constant. So, because slope is constant so, we can say this is a straight line.

So, that is how we say that is straight line and it passes through x_D, x_D and it will intersect at 45° line. Because 45° line means where there the x is equal to y . So, x_D, x_D will be there on a 45° line and this slope is R by $R + 1$ and the y intercept is x_D by $R + 1$ which is obtained by putting x_n is equal to 0 . So, this is the characteristics of the rectifying section operating line.

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Number of equilibrium stages in Rectifying Section

- ✓ A horizontal line is drawn to the left until it intersects the equilibrium curve at (y_1, x_1) .
- ✓ A vertical line is then dropped until it intersects the operating line at (y_2, x_1) .
- ✓ Horizontal and vertical lines are continued down the rectifying section.
- ✓ A **Partial condenser** can ideally act as an additional equilibrium stage by causing additional separation. So the total number of stages in the column is obtained by subtracting 1 from the stages obtained graphically.

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Now, after doing this let us see that how we can find out the number of equilibrium stages that, we can do this first we have this particular 45 degree line on a xy diagram. Please understand this both the x and y coordinates are the same scale only then we can make this 45 degree line. So, after me the same scale what we do? We draw the equilibrium curve from some given data and then we locate the x_D point, we understand because this is in terms of a lighter component from the naturally x_D will be nearer to one it could be 95 percent 98 percent like that. So, we find that it is on the top of this particular graph.

So, here we have x_D and from there what we do, we can either draw a straight line with a slope of R by R plus 1 or we can locate the intercept on the y axis as x_D by R plus 1; now that we have 2 points we can join them to get the straight line equation for the operating line of the rectifying section.

After drawing the operating line now what we do, that from this operating line we go straight to the equilibrium curve. Now why when we go from the straight to the x_D to the straight equilibrium curve what we find, we can locate the value of the y_1 . Because this x_D this is giving us that we are able to these are total condenser of your condenser is considering.

So, because total condenser we are finding that this is the value of the x_1 and y_1 and then what we do? After that we go to the operating curve equation. So, once we know x_1 we can find the value of the y_2 .

Now, once we know y_2 , we can find out from the equilibrium relationship the value of the x that this is the this is variable this particular horizontal line intersects the equilibrium curve, the corresponding value of the x is the x_2 . Once we know x_2 then we can find to the operating line, the value of the y_3 by drawing a horizontal line.

And then we find that from y_3 if variable it intersects the equilibrium curve, there we get the value of the x_3 ; that means, by using the operating line and the equilibrium curve alternately we are able to move down the column and find out the vapor and liquid compositions at various stages, and this particular construction is very simple it is called staircase construction.



And by this staircase construction, we are able to get the number of stages. Please minded that if we are using a partial condenser as I said, the partial condenser can also affect a additional separation and at the best it can also act as an equilibrium stage so, that whatever number of stages we count like we count the number of the horizontal lines as number of stages, because their horizontal line is bringing the 2 phases into equilibrium.

So, if there is a partial condenser, we take the top one as the partial condenser because the x_D will be coming out of the condenser and not directly from the column. So, and the actual number of equilibrium stages in the column will be taken to be the number counted here minus 1. So, that is how we take care of the partial condenser, this is not necessary or not required when we are using a total condenser.


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Total condenser and partial condenser

- ✓ Total condenser:
 - Does not act as stage
- ✓ Partial condenser
 - Acts as additional stage
 - At best, can act as an equilibrium stage.
 - Total number of stages in the column = Number of stages obtained - 1.

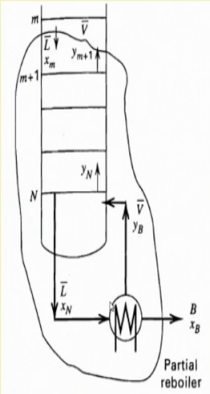
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Now total condenser does not act as a stage whereas, a partial condenser acts as a stage.

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Stripping Section





- ✓ Considers a portion of the stripping including the reboiler and extending up from stage N to stage $m + 1$, located somewhere below the feed.
- ✓ Numbered from the stage just below the feed stage, f , to the bottom stage.
- ✓ Overall material balance:


$$\bar{L} = \bar{V} + B$$
- ✓ Component material balance w.r.t lighter component:

$$\bar{L}x_m = \bar{V}y_{m+1} + Bx_B$$
- ✓ Solving for y_{m+1} , gives equation of *operating line*:

$$y_{m+1} = \frac{\bar{L}}{\bar{V}}x_m - \frac{B}{\bar{V}}x_B$$

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Now, then we go to the stripping section. In the stripping section what we find that we are now considering the stages which are below the feed stage against as we did for the rectifying section. In this case we are having the similar nomenclature the only difference is this in this case we are putting the liquid flow rate with a over bar.

And vapor flow rate with a over bar and rest of the nomenclatures for the mole fractions follow the same pattern that we are putting the stage number from which the particular

stream is coming out. And in this case what we do? We take the control volume which includes the a partial reboiler; and here what we do that we are writing the overall material balance as L is going into the system, V bodies V over bodies coming out of system and B is coming out of system.

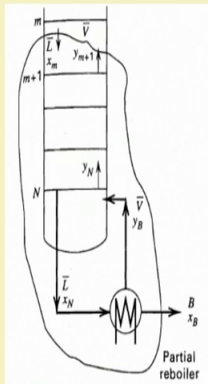
So, \bar{L} is equal to \bar{V} plus B and then we go for the component material balance in this what we find that this \bar{L} into x_m is the amount of component going in the system \bar{V} into y_{m+1} is the amount which is coming out of the system and B into x_B is the amount of component that is coming out of the system.

So, this becomes our material balance, please understand we are using the equal equilibrium relationship by on understanding that the any stream the vapor and the liquid coming out from the each of the stages are in equilibrium. That is if I choose any of these stages like x_n and y_n this x_n and y_n are in equilibrium.

So, now by again rearranging this particular equation, we get this equation which is the operating line for the stripping section. And in this particular equation we see it correlates the passing streams again, this y_{m+1} ; that means, this stream vapor stream and this liquid stream their compositions are being correlated by the operating line of the stripping section.

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Stripping Section



- ✓ Define boilup ratio, V_B as ratio of the vapor to bottoms flow rate, i.e., $\frac{\bar{V}}{B}$
- ✓ So

$$y_{m+1} = \frac{V_B + 1}{V_B} x_m - \frac{1}{V_B} x_B$$
- ✓ Energy balance:

$$\bar{L}h_{L,m} + \dot{Q}_B = \bar{V}h_{V,m+1} + Bh_B$$
- ✓ Combining with the overall mass balance we get

$$\frac{B}{\bar{V}} = \frac{h_{V,m+1} - h_{L,m}}{(\dot{Q}_B/D) - h_B + h_{L,m}}$$

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Now, in this case like we define reflux ratio, we can also define a boil of ratio as V over B and in terms of this V over B we can rewrite the operating line in this way. Now we can find this energy balance equations write this energy balance in this case we find that, we are including the reboiler duty on the liquid side because this reboiler duty is supplied into the system, to boil up the liquid.

So, this is going into the system along with the enthalpy which is carried by the liquid in to the system, and this is being balanced by the outgoing vapor enthalpy and the enthalpy carried by the bottoms and again we rearrange the equation, and from this we can find the value of B by V over B , which may also be used to find out the operating line equation.

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Operating line of Stripping Section

- ✓ Is a straight line.
- ✓ Passes through (x_B, x_B) . Thus it intersects the 45° line.
- ✓ Has slope of $\frac{V_B+1}{V_B}$
- ✓ Has y-intercept of $-\frac{1}{V_B}$

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Now we find that these operating line equations is a straight line as long as the boil of ratio is constant, and when we put x_m equal to x_B we find $y_m + 1$ is also equal to x_B ; that means, this operating line passes through x_B, x_B so, that one end of the operating line is on the 45 degree line and this has a slope of $V_B + 1$ by V_B and then y intercept of minus 1 by V_B ; that means, it will be below the 0 x axis.

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Number of equilibrium stages in stripping section

- ✓ A vertical line is drawn upward until it intersects the equilibrium curve at (y_B, x_B) , which represents the equilibrium mole fractions in the vapor and liquid leaving the partial reboiler which is assumed to act as an equilibrium stage.
- ✓ Staircase is now constructed by alternately moving vertically and horizontally between the equilibrium curve and the operating line.

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Now, here we have where the construction of the of the these stages for the stripping section, what we do again as we did for the rectifying section first we plot the xy diagram with the same scale and then we make this 45 degree lines. So, that the compositions x and y are same on the for this line, and then we locate the x B. Please understand x B here is on the left hand side corner because we are talking in terms of the more volatile component, its composition will be very less in the bottom product. So, it will be quite small here it may be 2 percent 5 percent etcetera.

So, we put it on this lower side x B x B and now what we do? What we will find that this x B if we have the partial reboiler, and is a partial reboiler may act as a equilibrium stage itself at the best. So, we what we do? To know the composition of the vapor coming out of the partial reboiler this liquid is taken to the equilibrium curve and here we find the composition of the vapor which comes out of the partial reboiler and that is y B that is a partial reboiler is acting as the as one equilibrium stage.

Then from this y B we go to the operating line to find out the value of x N because xn plus y B are the passing streams. Then once we know x N again we go; that means, now x N once we go to x N means, we have entered the inert stage now from that we again go to the equilibrium curve to get the composition of the vapor flow vapor, vapor which is flowing out of the inert stage and so, excellent wine are in equilibrium.

Now, once we know the y_n then we again we go to the n we go to the operating line of the stripping section, and from there we can know the composition of the x_{N-1} . And once you know x_{N-1} then we go back to the equilibrium curve to get the value of the y_{n-1} and that way if we use this operating line and the equilibrium curve alternately, we can traverse from the bottom to top of the stripping section and ultimately we move up the column up to the feed stage.

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Feed stage

- ✓ Reflux ratio and boilup ratio are related by the feed phase condition.
- ✓ Material balance:

$$F + L + \bar{V} = \bar{L} + V$$
- ✓ Energy balance:

$$Fh_F + Lh_{L,f-1} + \bar{V}h_{V,f+1} = \bar{L}h_{L,f} + Vh_{V,f}$$
- ✓ Assume change in enthalpies across the feed stage in the two sections to be small. Thus

$$h_{L,f-1} = h_{L,f} = h_L$$

$$h_{V,f+1} = h_{V,f} = h_V$$
- ✓ Hence

$$Fh_F + Lh_L + \bar{V}h_V = \bar{L}h_L + Vh_V$$

Or

$$(\bar{L} - L)h_L = Fh_F + (\bar{V} - V)h_V$$

The diagram shows a horizontal line representing the feed stage. Above the line, a blue arrow labeled 'V' points up and a black arrow labeled 'L' points down. Below the line, a black arrow labeled 'V-bar' points up and a blue arrow labeled 'L-bar' points down. A blue arrow labeled 'F' points from the left towards the line, and a blue arrow labeled 'f' points from the line to the right.

So, we find the slope of this particular line is this V/B plus 1 by V/B and if we extend this particular line downward, we will find the intercept will be minus 1 by V/B . Now we go to the feed stage now what is feed stage? Feed stage basically correlates the boil of ratio and the reflux ratio and we will see how it is done.

Now, first let us look at the feed stage; in the feed stage what we are having that the vapor is coming from the stripping section and going into the rectifying section, liquid is coming from rectifying section and going into the stripping section and we are putting different notations for the vapor and liquid flow rates in the 2 sections, and we are naming this stage as small f and capital F represents the feed flow rate.

So, this is the only addition which is happening in the feed stage these there was no external addition of any stream, for the other rectifying or the enriching or the stripping section. Now with this particular configuration we write the material overall material

balance as F plus L plus V which are this is the incoming stream to the feed stage and these are the outgoing stream the streams from the feed stage.

And this is the energy balance and what we do that we make an assumption here, we assume that that there is not much change in that temperature pressure across the feed stage so, that all these enthalpies can be taken to be the same. So, with this assumption what we do? wWe take that this whatever enthalpy is going from if this if I go with nomenclature here, we find that F this 1 is on the bottom and F minus from is our top.

So, with the nomenclature because we are counting from the top to bottom. So, we find that the there is not much change in the enthalpy as the streams cross the feed stage. So, we take the enthalpies of the liquid coming in and going out of the feed stage same as h_L , and the vapor enthalpy of the streams which are going into the and coming out of the feed stage as the same as h_V .

With this assumption we can modify this energy balance equation in this way, and we rearrangement of this will give us this particular equation.

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Feed stage

✓ Combining energy balance and overall mass balance over the feed stage we have

$$\frac{\bar{L} - L}{F} = \frac{h_V - h_F}{h_V - h_L} \equiv q$$

$q = \frac{\text{Enthalpy required convert one mole of feed to saturated vapor}}{\text{Molar enthalpy of vaporization of the feed}}$

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And then we really equation like this, and define a particular quantity q and q we can see that h_V minus h_F is the enthalpy required to convert one mole of feed to saturated vapor. Please understand in the column because we are assuming equilibrium all the vapors are taken to be at their dew point, and all the liquid are taken at to be there bubble point.

So, h_V minus h_L is the molar enthalpy of vaporization of the feed.

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q - value

- ✓ For a subcooled liquid

$$q = \frac{h_{fg} + C_{p,L}(T_b - T_F)}{h_{fg}}$$
- ✓ For a superheated vapor

$$q = \frac{C_{p,V}(T_d - T_F)}{h_{fg}}$$

- T_d, T_b and T_F : Dew point-, bubble point- and feed temperature respectively;
- h_{fg} : Enthalpy of vaporization;
- $C_{p,L}$ and $C_{p,V}$: Specific heats of the liquid and vapor respectively.

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Now, with this we find that this is the way we can also find the value of the q for a subcooled liquid that achieves is the enthalpy vaporization, and the sensible heat to convert the feed to the bubble point and is fg , and for the superheated vapor we simply subtract the sensible heat from the dew point from the dew point to the feed point feed temperature.

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Feed line or q line

- ✓ Instead of using the operating line for the stripping section, it is more common to use that for the rectifying section along with the feed line.
- ✓ Feed line or q -line:
 - Locus of the points of intersection of the operating lines for the rectifying section and the stripping section
- ✓ Operating line equations of rectifying section and stripping section:

$$V y = L x + D x_D$$

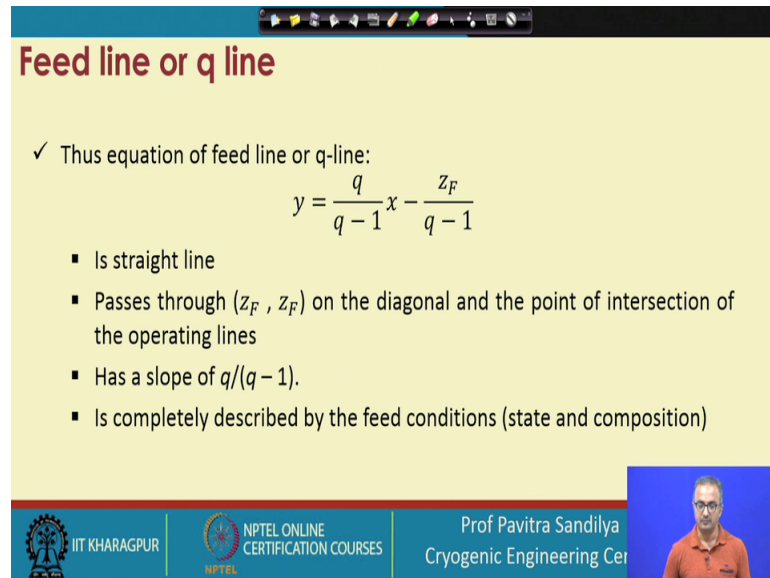
$$\bar{V} y = \bar{L} x - B x_B$$
 or $(\bar{V} - V) y = (\bar{L} - L) x + (D x_D + B x_B) = (\bar{L} - L) x + F z_F$

$$\frac{\bar{V} - V}{F} + 1 = \frac{\bar{L} - L}{F} =: q$$

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And now we have the q line we define the q line like this, that we consider these operating lines for the 2 sections and then subtract them and we get this particular equation in terms of the q.

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Feed line or q line

✓ Thus equation of feed line or q-line:

$$y = \frac{q}{q-1}x - \frac{z_F}{q-1}$$

- Is straight line
- Passes through (z_F, z_F) on the diagonal and the point of intersection of the operating lines
- Has a slope of $q/(q-1)$.
- Is completely described by the feed conditions (state and composition)

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And then what we do, we write the this equation this is the feed line or q line this gives us the locus of the intersection of the operating lines of the stripping section and the rectifying section.

So, by knowing this locus what we can do that, it helps us in constructing all the operating lines for both the stripping section and the rectifying section we shall see you later, and we find that if I put x into Z F then y is equal to Z F and with constant q this is a the straight line equation. So, this straight line passing through ZF slope of q by q minus 1 and it is completely described by the feed conditions that is why it is called the feed design.


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Feed condition

- (a) Subcooled liquid feed,
- (b) Bubble point liquid feed
- (c) Partially vaporized feed,
- (d) Dew-point vapor feed, and
- (e) Superheated-vapor feed.

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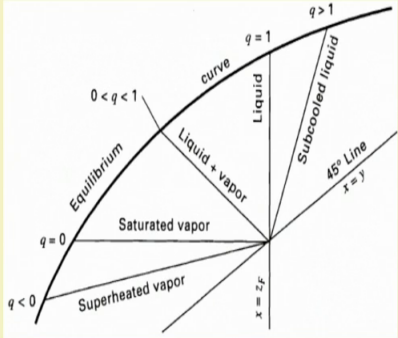




Now, there can be various types of feed possible sub cooled liquid bubble point and liquid feed, and partially vaporized feed dew point feed.

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Effect of feed condition on (slope of)q -line

Feed quality	q	Slope of q -line [$q/(q-1)$]
Subcooled liquid	>1	>1
Saturated liquid	1	∞
Liquid and vapor	$0 - 1$	<0
Saturated vapor	0	0
Superheated vapor	<0	$0 - 1$



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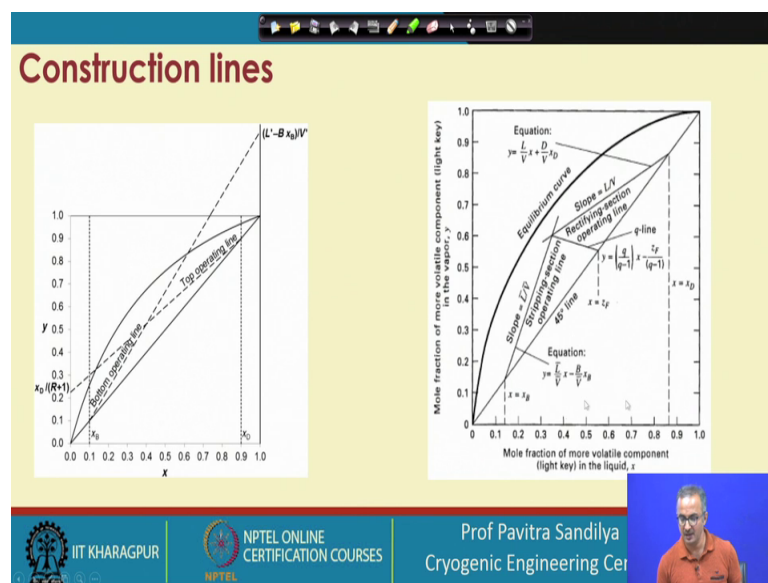


And depending on the different type of the feed, we find we have different values of q . You can easily find out that the q value will be more than one for sub cooled liquid, and so the slope of this thing will be more than one the saturated vapor will be one for vapor liquid mixture it will be between 0 and 1 for saturated vapor to be 0 and superheated vapor to be less than 0.

So, with this kind of various types of feed will determine the type of the q value, and with the different of q value we will get different slopes of the feed design and here we can see in this figure that if we have subcooled liquid, the slope will be this is the q line for the subcooled liquid, this is q line for the saturated liquid this is for the vapor liquid mixture, these are saturated vapor and this is for the superheated vapor.

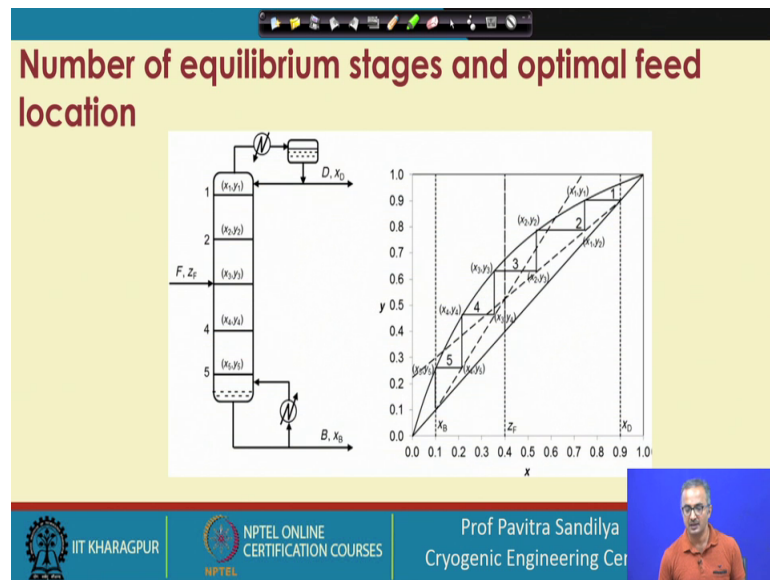
So; that means, the stripping section of operating line and the defensive the operating line will be intersecting at one of in one of these lines.

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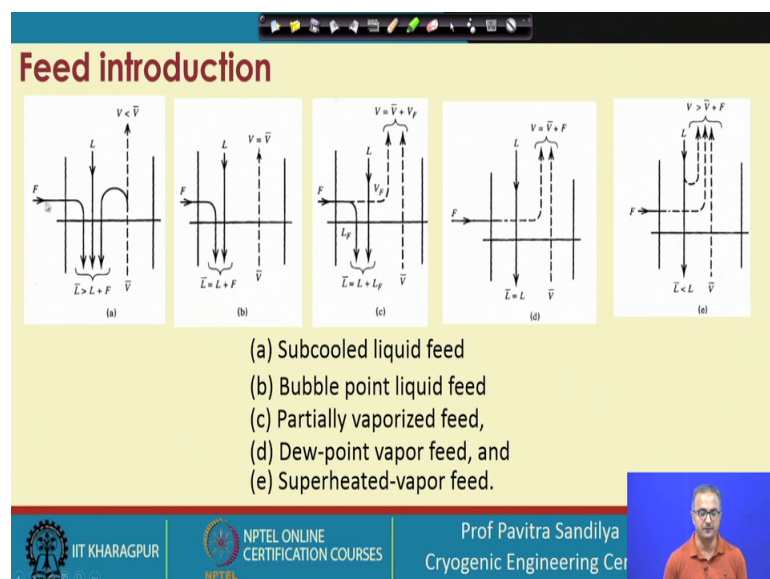
Now, here we see that once we have these operating lines these 2 operating lines, this particular cross section will be on this feed line and here in this particular figure we see that once we locate the x_D point x_B point and the Z_F point, we can draw the feed line we can draw the operating line from the rectifying section, and from this point of intersection if I join the x_B x_B point, I will get the operating line for the stripping section. That means, I do not need to construct the operating that would stripping section separately simply by drawing the feed line, and the operating line of the rectifying section, I can generate the operating line for the stripping section.

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And once we have done that then what we can do simply do that, we can start making these stages as I explained earlier I can keep making these staircases to get the number of stages in the total column. Only thing one has to remember that when I am above the feed, I will be using the operating line for the rectifying section and as soon as we cross the feed we shall be using the operating line for the stripping section, and that is how we can construct the staircases from the top to the bottom.

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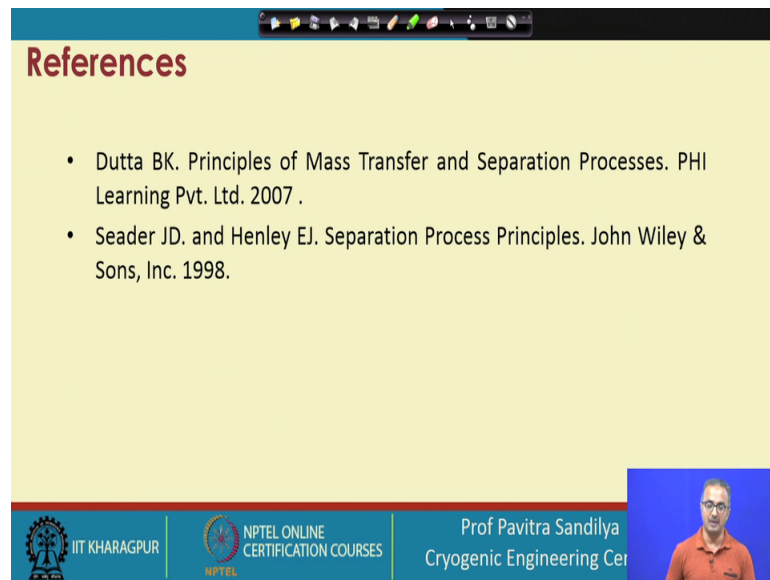
And we have different types of feed introduction; like if you have sub cooled feed then the feed will be going to the bottom then if we have a bubble point feed it will also come to the lower plate, if you have a partially vaporized feed then we will find the vapor portion will move up the column whereas, the liquid portions will come down the column, we have dew point feed and the superheated field, in both the cases we shall find that this will be moving up the column.

The difference is this when this sub cooled liquid is goes you may goes then it will also try to liquefy some of the vapor. So, that we find that some of the liquid will come from the vapor to which is not the case, when we are putting the saturated liquid. This sub cooling is also helping us to get some condensation of the vapor whereas; in this case we find when we put superheated vapor, some of the superheat is used to re vaporize the liquid so, that some of the liquid will get re vaporized which is not the case when we put the saturated vapor.

So, that is how they become different and we find that the how the liquid flow rates in the vapor flow rates get affected in the 2 sections by the type of the particular or the feed condition, that we find that for example, in this particular case we find that is this the liquid flow rate in the stripping section is more than the liquid flow rate in the rectifying section.

Because the feed adds to this particular flow rate to give us the stripping section liquid flow rate, and similar logic can be applied to find out the or the compare the liquid and vapor flow rates in the 2 sections.

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References

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- Seader JD. and Henley EJ. Separation Process Principles. John Wiley & Sons, Inc. 1998.

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The slide features a yellow background with a dark blue header and footer. A small video inset in the bottom right corner shows a man in a red shirt. The footer contains logos for IIT Kharagpur and NPTEL, along with the name and affiliation of the professor.

So, this is a brief introduction to these distillation column analysis and these 2 books may be used for detail for more detail.

Thank you.